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GYROSCOPIC EFFECT IN MACHINE WORKING ASSEMBLIES

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This paper discusses and calculates the impact of the gyroscopic effect on the increase in the agricultural machine working assemblies' load on bearings of the chaff cutter type. This effect occurs under natural field operational conditions of this type of machine either during the change in direction of its movement or moving over irregular surface and is caused by a sudden change in the axis direction of quickly rotating masses. In a form of graph, there is a presentation of a mathematical model and exemplary results of simulation calculations for selected parameter values related to the movement and operation of machines with a high-speed drum. Calculations were conducted on the basis of analysis of technical data of working machines of the chaff cutter type. Conducted analysis of the agricultural machine working assemblies' load on bearings showed that these loads may temporarily increase even by ten times in case of the machine turn and eight times in case of moving over irregular of surface, considerably influencing their lifetime.

Keywords: increased load on bearings; high-speed machine working assemblies; bearing load in cutting assemblies; bearing load in working machines; mathematical model

Working assemblies of many machines and devices comprise high-speed elements with a high moment of inertia, rotating around a dynamic symmetry creating the so-called gyroscope, their movement being called the gyroscopic proper motion.

When a gyroscope axis is motionless, machine bearings are loaded with interaction:

- working one, resulting from an operation performed by a rotating element;
- gravitational, resulting from interaction with gravitational field.

Gyroscopic effect occurs in cases when the axis of quickly rotating masses would change its direction.

Such a phenomenon occurs in working machines of either chaff cutter type or combine harvester type during turning or driving over irregular surfaces. Subsequently, there is an additional, quick-changing load on bearings in cutting drums of a chaff cutter or rotating bearings of threshing assemblies in combine harvesters, in which there is a tendency of changes in the direction of a gyroscope axis. This phenomenon also occurs in bearings of ship propulsion turbine during changing of course when it moves together with the vessel around the vertical axis or in case of strong swaying due to waves.

In contemporary literature, there is no detailed analysis of the gyroscopic effect impacts on the balance of forces load on the bearing elements. Subject area related to kinematics and dynamics of machine working assemblies' movement has already been discussed in a detailed manner; however, modelling of the working processes has never taken the gyroscopic effect into consideration. Flizikowski et al. (2015), Keska and Gierz (2011), Zastempowski and Bochat (2014, 2015, 2016) have dealt with this issue.

Multiple scientific studies (Ligaj and Szala, 2010; Strzelecki et al., 2016) have presented the issues related to design and analysis of construction resistance, rules for manufacturing execution system use, numerical and mathematical modelling, and construction optimization.

Vital issue, with which the designers must cope, lies in appropriate design of machines equipped with quick-rotating working assemblies. It is possible if all dependencies and relations resulting from the impacts of the gyroscopic effect on the bearing load are fully recognized and taken into account.

Due to universality of occurrence and availability of input data for simulation calculations, the analysis was conducted for a working machine of a self-propelled chaff cutter type. It was equipped with a high-speed drum cutting assembly located in the machine body. Special attention should be paid to this issue, as subject of cutting assemblies is very topical, since they represent the basic working assemblies in a large group of agricultural machines for crop harvesting for energetic purposes (biomass), fodder, as well as consumption.

The mathematical model developed in the article takes fully into consideration the cases of gyroscopic effect occurring as a result of the machine turning and running over irregular surface under field operational conditions.

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Material and methods

The gyroscopic effect during the turning of the chaff cutter

Fig. 1 presents a scheme of rotating chaff cutter drum [2] mounted on the shaft [3] with a determined coordinate system. The shaft with drum is located above the vehicle front axis and is mounted in points *A* and *B*. In the drum gravity centre [0], there is centred a dextrorotatory Cartesian coordinate system *xyz*, so that the system's axes follow the main drum's inertial axes. The mass moment of inertia towards these axes amounts to: J_x, J_y, J_z, respectively.

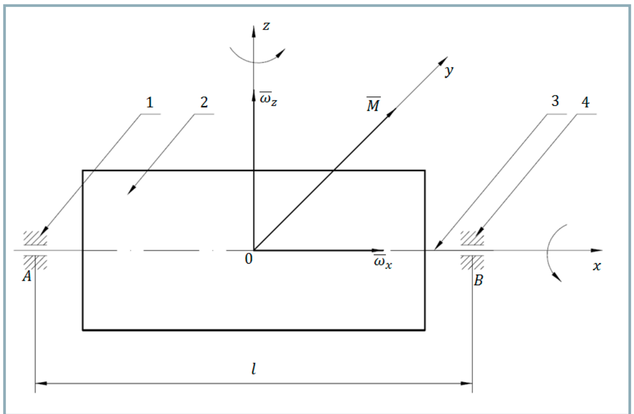

Fig. 1 Gyroscopic effect during the chaff cutter left turn (own study)
1 – place of the shaft support (left bearing A); 2 – rotating cutting drum; 3 – shaft; 4 – place of the shaft support (right bearing B)

The gyroscope is created by the drum rotating at an angular speed ω_x around the axis *x*. The axis *y* follows the direction of a vehicle rotation at the speed *v*. A case of turning the vehicle to the left, corresponding to the angular speed described with vector $\overline{\omega}_z$ in relation to axis *z*, will be analysed.

For any vector $\overline{H}$ at a momentary rotational momentum ω, the derivative of that vector will take the following in regard to time *t* (Landau and Lifszyc, 2012):

$$\frac{d\overline{H}}{dt} = \overline{\omega} \times \overline{H} \tag{1}$$

Therefore, by means of an analogy to the gyroscope angular momentum $\overline{K}$, the following expression (Eq. 2) was received:

$$\frac{d\overline{K}}{dt} = \overline{\omega}_z \times \overline{K} = \overline{\omega}_z \times \left(J_x\overline{\omega}_x + J_z\overline{\omega}_x\right) \tag{2}$$

Taking into account that $\overline{\omega}_z \times \overline{\omega}_z = 0$, and the fact that the derivative of the angular momentum after a time equals to the moment of external forces $\overline{M}$ acting on the gyroscope, the dependence describing the gyroscopic effect will have the following form:

$$\overline{M} = \overline{\omega}_z \times J_x\overline{\omega}_x \tag{3}$$

Analysing the chaff cutter movement during its turning to the left, the direction of the momentum vector $\overline{M}$ coincides with the axis *y*, and three vectors $\overline{\omega}_z$, $\overline{\omega}_x$, $\overline{M}$ form the dextrorotatory system. Thus, it is possible to describe the absolute value of the moment $\overline{M} = \left|\overline{M}\right|$ by:

$$M = J_x\,\omega_x\,\omega_z \tag{4}$$

where:
ω_x – is described by the dependency $\omega_x = \left|\overline{\omega}_x\right|$
ω_z – is described by the dependency $\omega_z = \left|\overline{\omega}_z\right|$
M – is described by the dependency $M = \left|\overline{M}\right|$

The geometry scheme of the chaff cutter turning is presented in Fig. 2.

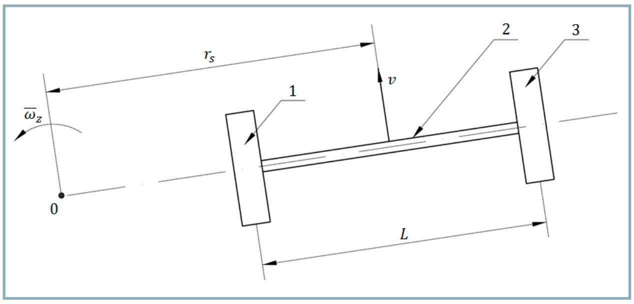

Fig. 2 Geometry scheme of the chaff cutter turning to the left (own study)
1 – vehicle left wheel; 2 – vehicle axis; 3 – vehicle right wheel

By analysis of this vehicle type movement at the speed v around the point 0, the value of the angular speed ω_z at the turning radius r_s may be established as:

$$\omega_z = \frac{v}{r_s} \tag{5}$$

The mass moment of inertia J_x can be described with the following dependence:

$$J_x = r_b^2\, m \tag{6}$$

where:
r_b – radius of gyration, i.e. the radius on which it is pointwise located, with mass equal to the mass of the drum
m – mass of the drum

The force of gravitational interaction G_g on a single bearing amounts to:

$$G_g = \frac{1}{2} mg \tag{7}$$

where:
g – gravitational acceleration

However, the effect of the gyroscopic interaction force Gż on the bearing can be described by the dependence:

$$G_{\dot{z}} = \frac{M}{l} \tag{8}$$

where:
M – moment described by Eq. 4
l – spacing of the drum bearings (Fig. 1)

Joining the dependences (Eqs. 5–8), the influence of the gyroscopic effect $G_{\dot{z}}$ on the bearing can be determined in relation to gravitational interactions G_g in the form of:

$$\frac{G_{\dot{z}}}{G_g} = \frac{\beta^2}{2\alpha}\frac{d}{l}\frac{d}{L}\frac{\omega_x \nu}{g} \tag{9}$$

The dimensionless parameter α in Eq. 9 describes the twist radius r_s dependent on the spacing of machine wheels L; the parameter β describes the mass distribution of the chaff cutter drum in accordance with Eqs. 10 and 11:

$$\alpha = \frac{r_s}{L} \tag{10}$$

$$\beta = \frac{2r_b}{d} \tag{11}$$

where:
d – drum diameter
β – number from the range (0; 1) describing the splitting of the drum mass

In such a manner, the quotient $\frac{G_{\dot{z}}}{G_g}$ will be calculated as a product of dimensionless expressions.

The gyroscopic effect during the movement of the chaff cutter over irregular surface

Fig. 3 presents the analogical mechanical system as Fig. 1. The drum mounted on the shaft rotates at the angular speed ω_x. The case of left wheel movement over irregular surface, which corresponds to the angular speed described with the vector $\overline{\omega}_y$ with direction of axis y, will be subjected to analysis.

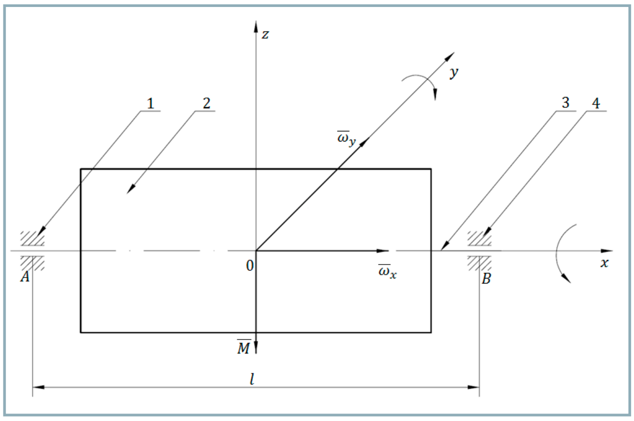

Fig. 3 Gyroscopic effect on the left wheel of the chaff cutter moving over irregular surface (own study)
1 – place of the shaft support (left bearing A); 2 – rotating cutting drum; 3 – shaft; 4 – place of the shaft support (right bearing B)

In this case, the angular momentum of gyroscope can be described as:

$$\overline{K} = J_x\,\overline{\omega}_x + J_y\,\overline{\omega}_y \tag{12}$$

The derivative of the moment of momentum in relation to the time amounts to:

$$\frac{d\overline{K}}{dt} = \overline{\omega}_y \times \left(J_x\,\overline{\omega}_x + J_y\,\overline{\omega}_y\right) = \overline{\omega}_y \times J_x\,\overline{\omega}_x + \overline{\omega}_y \times J_y \tag{13}$$

Since:

$$\overline{\omega}_y \times J_y\,\overline{\omega}_y = 0 \tag{14}$$

and

$$\frac{d\overline{K}}{dt} = \overline{M} \tag{15}$$

the gyroscopic effect on the wheel during movement over the irregular surface can be described by the following equation:

$$\overline{M} = \overline{\omega}_y \times J_x\overline{\omega}_x \tag{16}$$

Direction of the moment $\overline{M}$ of the left wheel during movement over irregular surface corresponds with the axis z. Three vectors $\overline{\omega}_x$, $\overline{\omega}_y$ and $\overline{M}$ form a dextrorotary system. Therefore, the absolute value of the moment $M = \left|\overline{M}\right|$ can be described by dependence:

$$M = J_x\,\omega_x\,\omega_y \tag{17}$$

The value of angular speed ω_y can be determined by means of analysis of the movement process over irregular surface in accordance with Fig. 4.

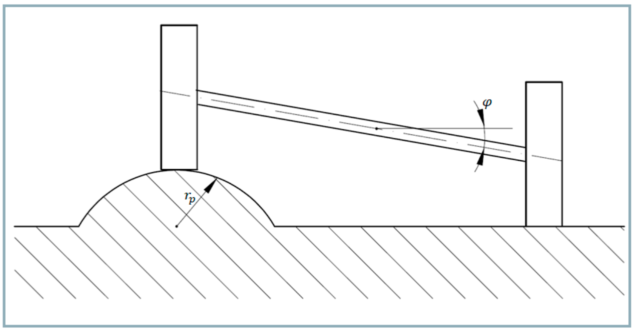

Fig. 4 General scheme of the chaff cutter left wheel movement over irregular surface with radius r_p (own study)

Half of the roller with a radius r_p has been assumed as the irregularity model. In the middle of the obstacle – point P – there was located the system of coordinates hs. The monitoring process (Fig. 5) of the wheel track with the radius r_k began in the moment of the wheel's contact with the obstacle in point A. Subsequently, there occurs a rapid raising of wheel from the ground, which can be described with a derivative dh/ds. For a driving medium marked with point K, the coordinates a, b were assumed.

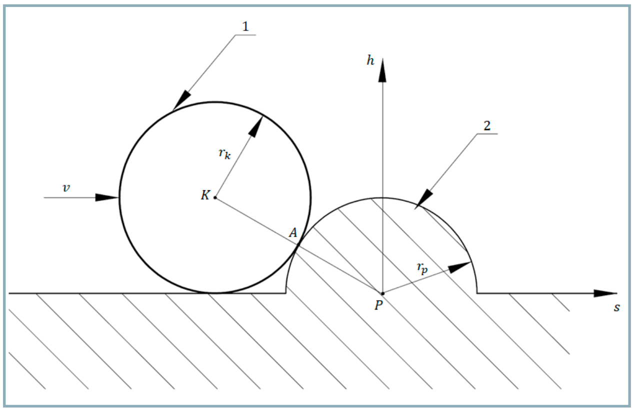

Fig. 5 Movement geometry of the left wheel over irregular surface (own study)
1 – machine wheel; 2 – surface irregularity

The coordinate b amounts to:

$$b = r_k \tag{18}$$

while the coordinate a is determined by the following equation:

$$a^2 + b^2 = (r_k + r_p)^2 \tag{19}$$

from which follows:

$$a = -\sqrt{2r_k r_p + r_p^2} \tag{20}$$

The inclination coefficient k of the segment KP was determined from the following dependence:

$$k = \frac{b}{a} \tag{21}$$

Since the tangent in point A is perpendicular to the section KP, it means that:

$$\frac{dh}{ds} = -\frac{1}{k} \tag{22}$$

Taking the Eqs. 18–21 into account, the derivative dh/ds can be written as:

$$\frac{dh}{ds} = \sqrt{2\frac{r_p}{r_k} + \left(\frac{r_p}{r_k}\right)^2} \tag{23}$$

For the purposes of the below analysis it has been assumed that the angular speed of the chaff cutter's axis is equal to the angular speed ω_y of the gyroscope axis.

Since:

$$\omega_y = \frac{d\varphi}{dt} \tag{24}$$

and the differential $d\varphi$ can be obtained with dependence:

$$d\varphi = \frac{1}{L} dh \tag{25}$$

Eq. 24 will be of the following form:

$$\omega_y = \frac{1}{L}\frac{dh}{dt} = \frac{1}{L}\frac{dh}{ds}\frac{ds}{dt} = \frac{dh}{ds}\frac{\nu}{L} \tag{26}$$

where:
ν – machine movement speed
L – machine wheel track

Taking the Eq. 23 into consideration, Eq. 26 can be written as follows:

$$\omega_y = \gamma \frac{\nu}{L} \tag{27}$$

where:
γ – coefficient of the surface irregularity described by the following dependence (Eq. 28):

$$\gamma = \sqrt{2\frac{r_p}{r_k} + \left(\frac{r_p}{r_k}\right)^2} \tag{28}$$

The surface irregularity coefficient γ is a function of the irregularity radius quotient r_p to the ground wheel radius r_k. Fig. 6 shows the curve describing this dependence.

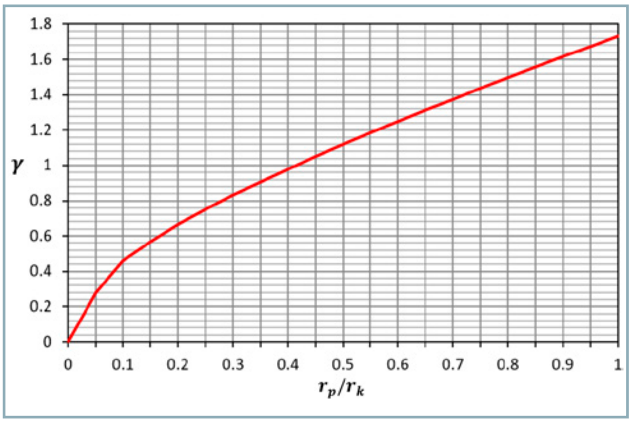

Fig. 6 Graph of the surface irregularity coefficient as a function of the irregularity radius quotient r_p and vehicle ground wheel radius r_k (own study)

Considering the Eq. 28, it is possible to determine the gyroscopic effect during movement over irregular surfaces on the basis of the following equation:

$$\frac{G_{\dot{z}}}{G_g} = \frac{\gamma\beta^2}{2}\frac{d}{l}\frac{d}{L}\frac{\omega_x \upsilon}{g} \tag{29}$$

Results and discussion

For the purposes of simulation calculations, there were assumed the real constructional features and parameters of the following chaff cutters: New Holland FR Forage Cruiser; Claas Jaguar 900; and John Dear series 8000.

In regard to numerical calculations according to constructional and kinematic parameters of the selected working machines, the following was assumed:

a) dimensionless forms of constructional coefficients:

$$\beta = 0.7; \quad \frac{d}{l} = 0.7; \quad \frac{d}{L} = 0.2$$

and α in the interval (0.5; ∞);

b) dimensionless forms of kinematic coefficients $\frac{\omega_x \upsilon}{g}$, for which the range of values was determined as $\frac{\omega_x \upsilon}{g} \in (10; 90)$.

Fig. 7 presents the graph showing the increase in the load on the cutting drum bearing elements during its turning in the form of relation of the gyroscopic effect $G_{\dot{z}}$ to the gravitational reaction G_g dependent on the machine movement speed for specific coefficients α according to Eq. 9. The value $\alpha = 0.5$ describes the smallest possible turning radius; the movement of the vehicle without turning occurs when $\alpha = \infty$.

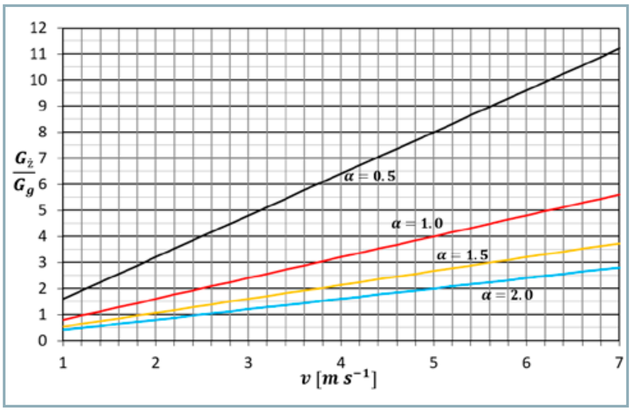

Fig. 7 Graph presenting the relation of the gyroscopic effect $G_{\dot{z}}$ to gravitational reaction G_g dependent on the machine movement speed during its turning (own study)

Analysing the results obtained from simulation calculations, it is possible to establish that the dimensionless parameter of kinematic values $\frac{\omega_x \upsilon}{g}$ and α the parameter a describing the turning radius (which equals half of the wheel track $r_s = \frac{L}{2}$), with a minimum value of $\alpha = 0.5$, have a significant impact on the value $\frac{G_{\dot{z}}}{G_g}$.

The force $G_{\dot{z}}$ occurring during the turning of this type of vehicle has a direction consistent with the gravitational force G_g. For the case presented in Fig. 1, the forces having an effect on the bearing A amount to:

$$G_A = G_{\dot{z}} - G_g$$

while forces having an effect on the bearing B amount to:

$$G_B = G_{\dot{z}} + G_g$$

Fig. 8 shows the diagram of increase in load on the chaff cutter bearings during moving of its wheels over the irregular surface under field operational conditions. The diagram is presented in the form of relationship of the gyroscopic effect $G_{\dot{z}}$ to gravitational force G_g dependent on the machine operational speed for the determined relations of the wheel radius r_k and the ground surface irregularity radius r_p. The lower the value of the expression $\frac{r_p}{r_k}$, the smaller the surface irregularities.

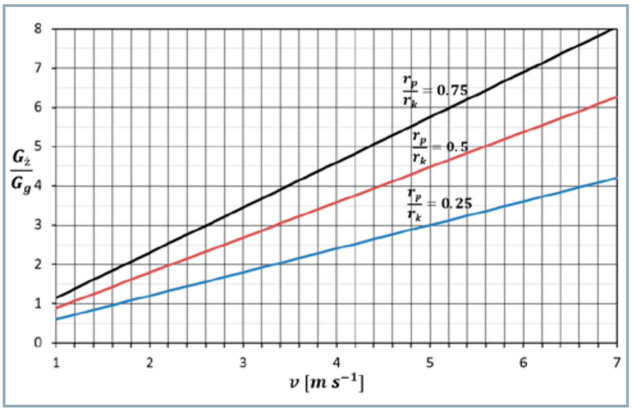

Fig. 8 Graph of the relation of the gyroscopic effect $G_{\dot{z}}$ to the gravitational fore G_g dependent on the machine movement speed during monitoring of its movement over irregular surface (own study)

The force $G_{\dot{z}}$ occurring during its moving over the surface irregularities is orthogonal to the force G_g. The resultant force G impacting the bearing amounts to:

$$G = \sqrt{G_{\dot{z}}^2 + G_g^2} \tag{30}$$

Considering the known literature, authors do not deal with a detailed impact analysis of the gyroscopic effect on the balance of forces interacting on the fast-rotating machines bearings in motion working assemblies. The subject widely taken up by researchers is mainly related to the analysis and strategy of the agricultural machinery maintenance and repair (Pourdarbani, 2019), deformation and wear of working tools in agricultural and forestry machinery (Ťavodová et al., 2018), determination of operating parameters and functioning effectiveness (Moinfar and Shahgholi, 2018), and investigation of hydraulic systems in agricultural machinery (Tkáč et al., 2017) without analysis of additional load in the machinery working assemblies.

The gyroscopic effect increases the load on fast-rotating bearing elements, which can result in their faster wear or damage. That is a reason why it is necessary to take this phenomenon into account in terms of both design of working assemblies' bearings, and development of a preventive system for technical facilities exploitation, which has not been done so far and was presented by Knopik and Migawa (2017), and Knopik and Migawa (2018). The increased load on technical facilities may also result in their increased impact on the environment (Karwowska et al., 2013; Karwowska et al., 2014).

Conclusion

One can encounter the impacts of the gyroscopic effect during the everyday exploitation of the selected constructions of machines, making the subject matter quite topical.

The increased load on the bearing elements can result in adverse effect on the durability of machine working assemblies.

Considering the results of the analysis of simulation calculations conducted for the selected type of self-propelled chaff cutters, the gyroscopic effect can increase the bearing load by more than ten times in case of turning, and approximately by eight times in case of moving over irregular surface.

Analysing the results obtained from the simulation calculations, it may be found that, just like in the case of machine turning, the kinematic coefficient $\frac{\omega_x \upsilon}{g}$ and the coefficient γ connected to the irregularity of surface geometry have a decisive impact on the value $\frac{G_{\dot{z}}}{G_g}$.

Having the models presented in the paper at disposal, the designers of machines and equipment can more carefully and precisely design the bearings of rotating elements burdened with a gyroscopic effect. It will enable decreasing the failure rate of this machinery, which will be reflected in lowering of the costs for exploitation and maintenance.

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